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Keelan

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(54) **IMAGING SYSTEMS WITH REFERENCE PIXELS FOR IMAGE FLARE MITIGATION**

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H04N 9/04	(2006.01)
H04N 5/365	(2011.01)
H04N 5/367	(2011.01)

(52) **U.S. Cl.**

CPC ***H01L 27/14685*** (2013.01); ***H01L 27/14621*** (2013.01); ***H01L 27/14623*** (2013.01); ***H04N 5/3572*** (2013.01); ***H04N 5/3651*** (2013.01); ***H04N 9/045*** (2013.01); *H04N 5/367* (2013.01)

(58) **Field of Classification Search**

None

See application file for complete search history.

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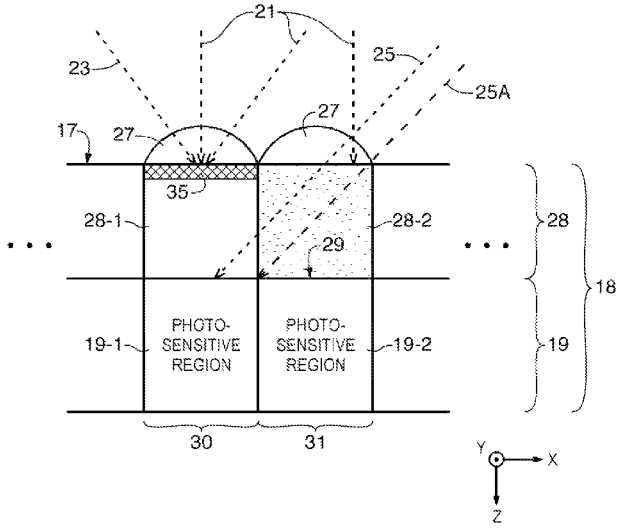
(57) **ABSTRACT**

Imaging devices may include processing circuitry, a lens, and an array of image sensor pixels and reference pixels. The array may receive direct image light and stray light from the lens. The image sensor pixels may include clear color filter elements and the reference pixels may include opaque color filter elements. The opaque color filter elements may block direct image light from being captured by the reference pixels. The image sensor pixels may generate pixel values in response to the direct image light and the stray light whereas the reference pixels may generate reference pixel values in response to the stray light. The processing circuitry may mitigate stray light effects such as local flare and veiling glare within the imaging system by adjusting the pixel values based on the reference pixel values. The imaging system may be calibrated in a calibration system for generating stray light calibration data.

19 Claims, 9 Drawing Sheets



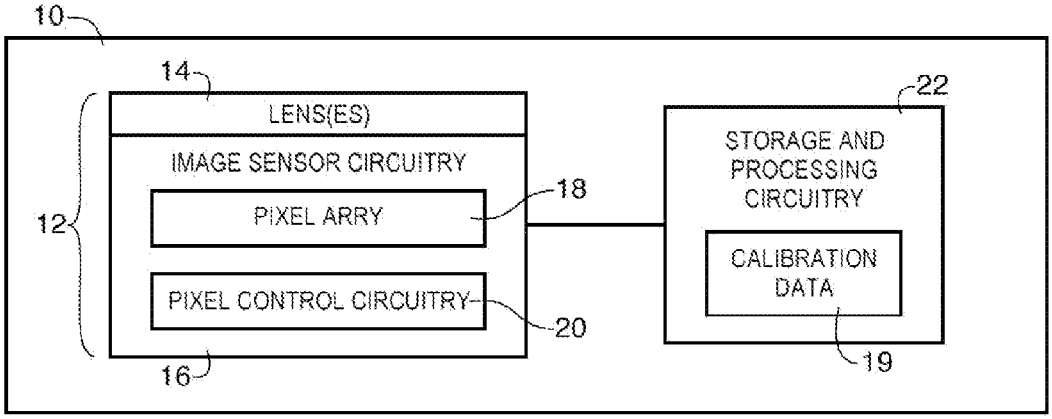

10
14
LENS(ES)
IMAGE SENSOR CIRCUITRY
PIXEL ARRY
PIXEL CONTROL CIRCUITRY
12
16
18
20
22
STORAGE AND PROCESSING CIRCUITRY
CALIBRATION DATA
19
Y
X
Z

FIG. 1

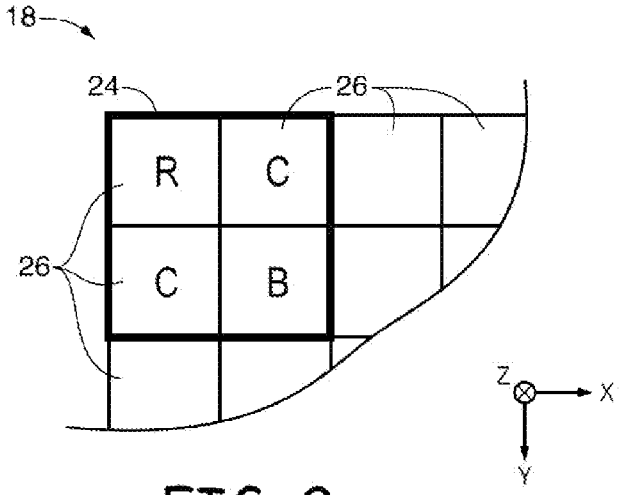

18
24
26
R
C
C
B
26
Z
X
Y

FIG. 2

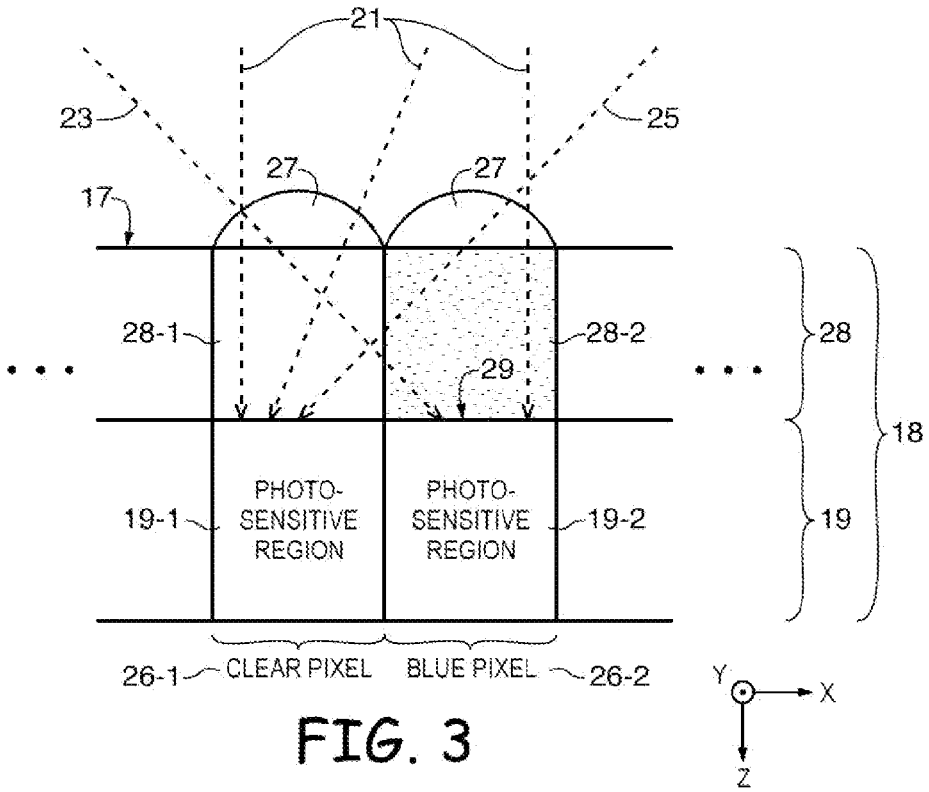
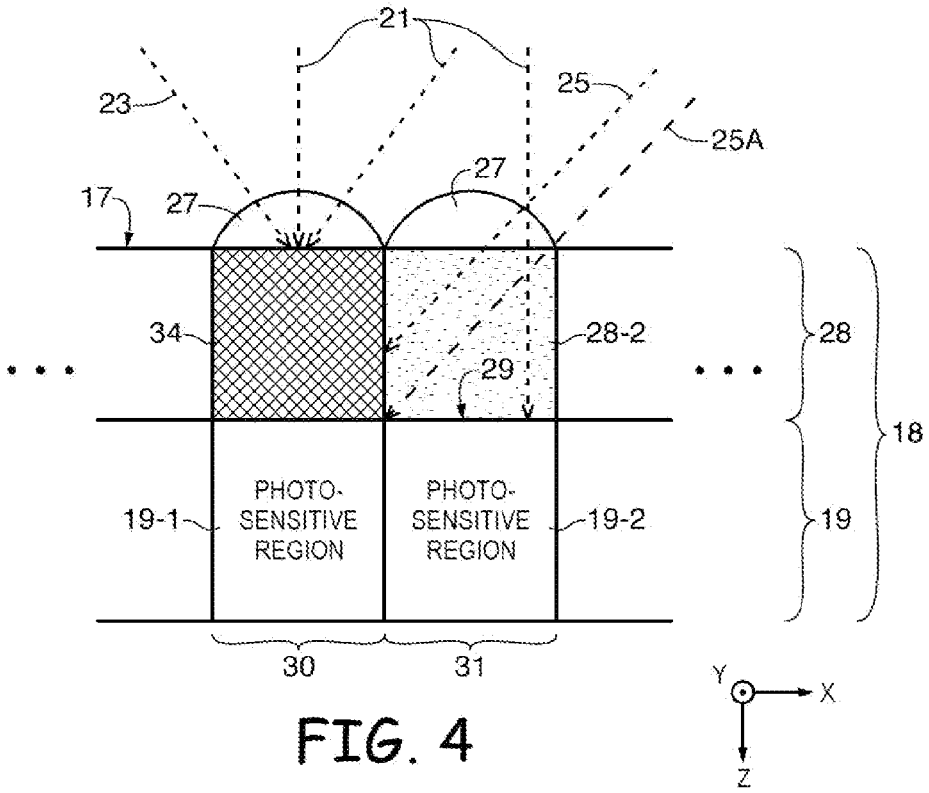

21
23
25
27
27
17
28-1
28-2
29
28
18
19
19-1
PHOTO-SENSITIVE REGION
PHOTO-SENSITIVE REGION
19-2
26-1
CLEAR PIXEL
BLUE PIXEL
26-2
Y
X
Z

FIG. 3


21
23
25
25A
27
27
17
34
28-2
29
28
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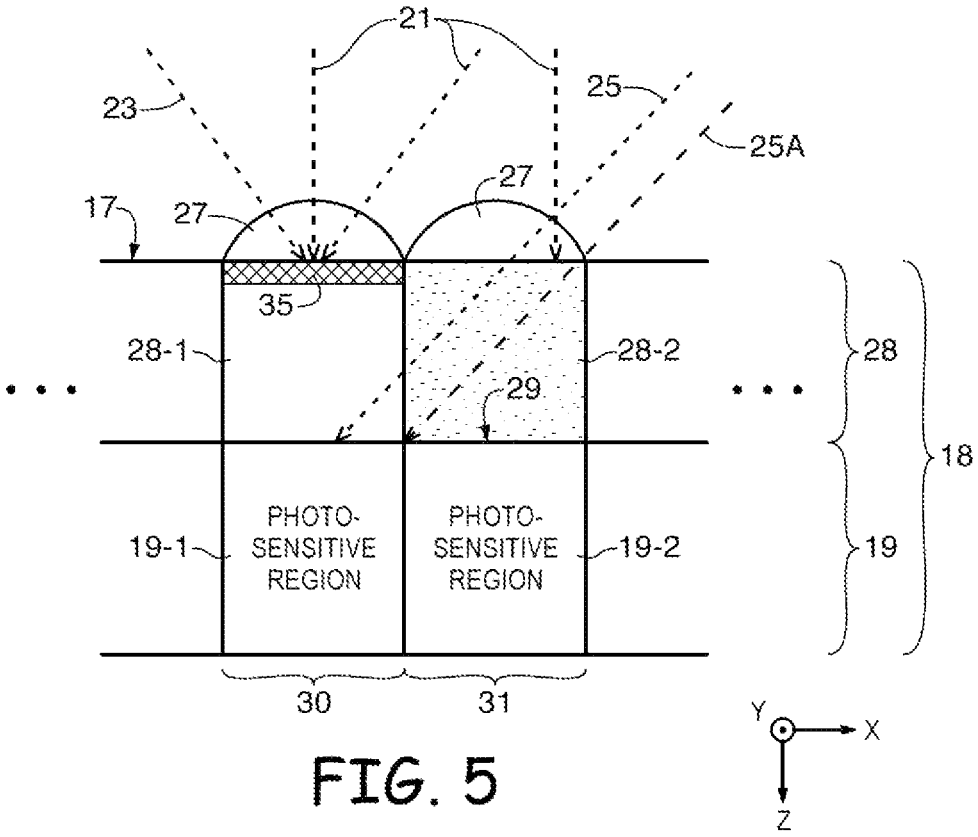
19-1
PHOTO-SENSITIVE REGION
PHOTO-SENSITIVE REGION
19-2
30
31
Y
X
Z

FIG. 4


21
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28-1
28-2
29
28
18
19
19-1
PHOTO-SENSITIVE REGION
PHOTO-SENSITIVE REGION
19-2
30
31
Y
X
Z

FIG. 5

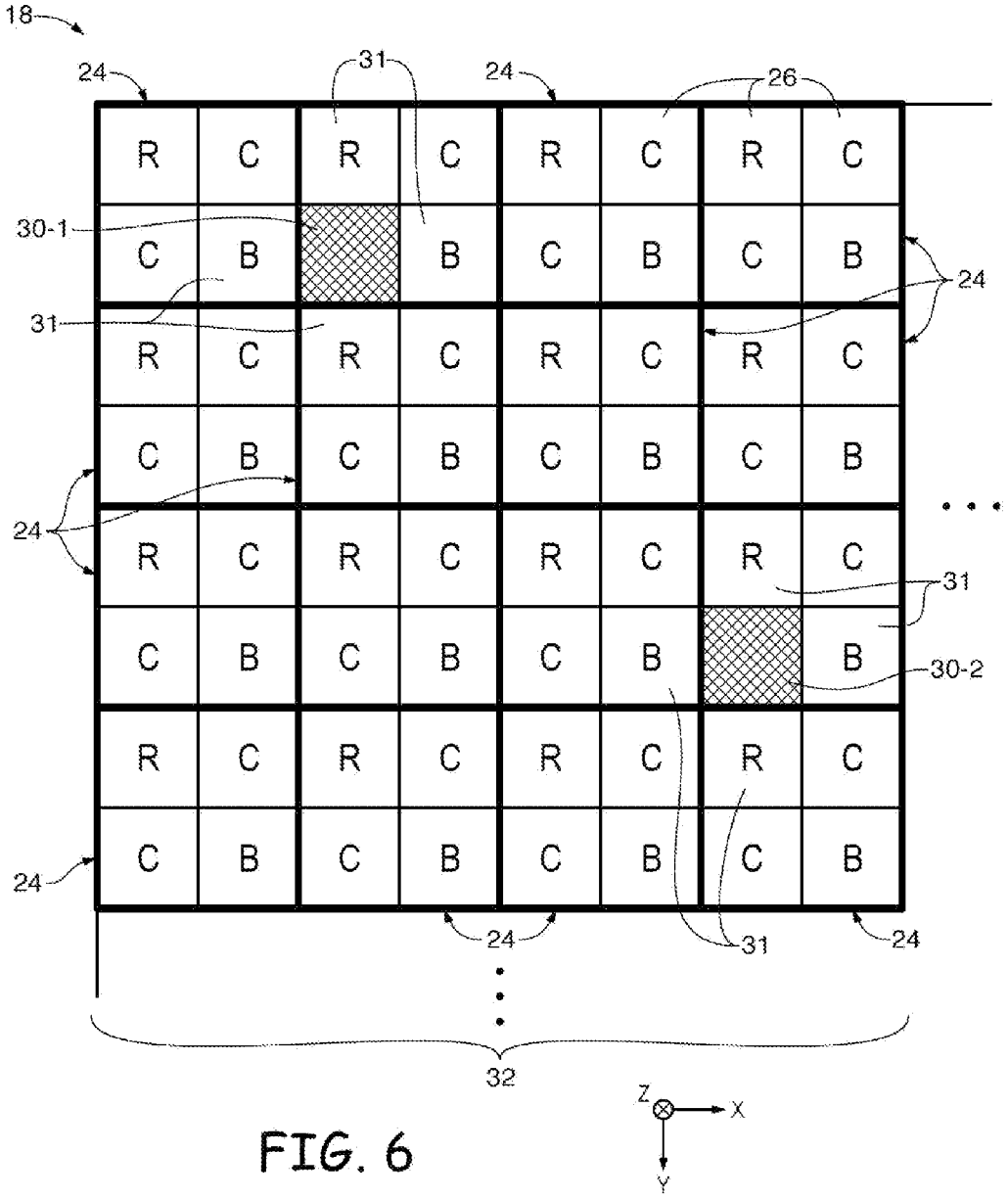

FIG. 6

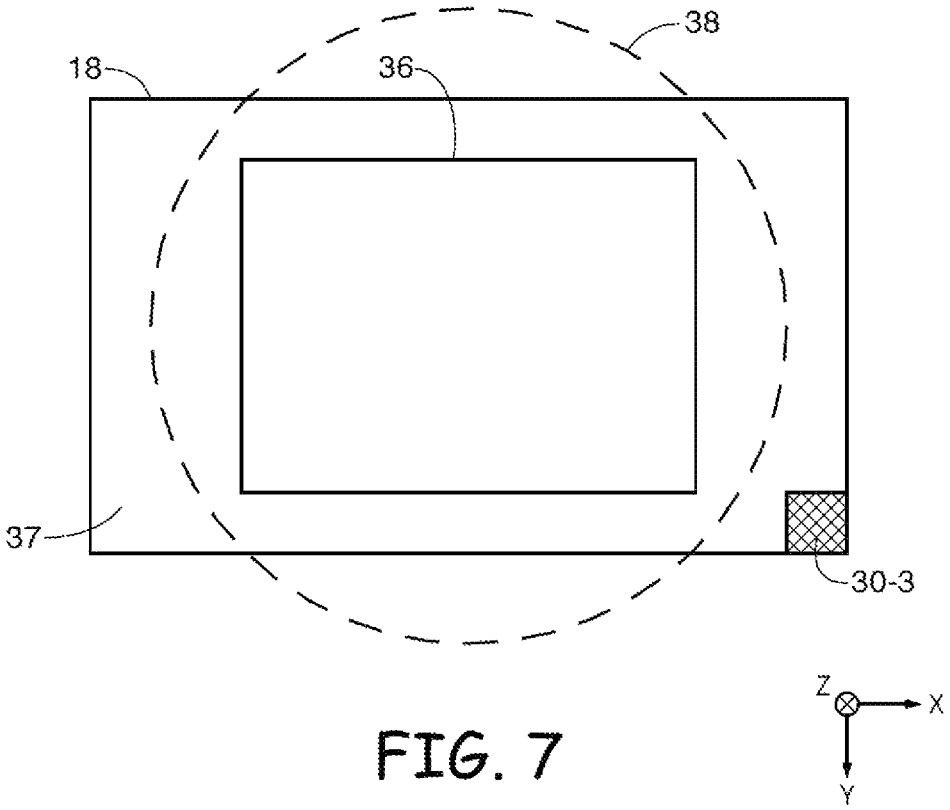

FIG. 7

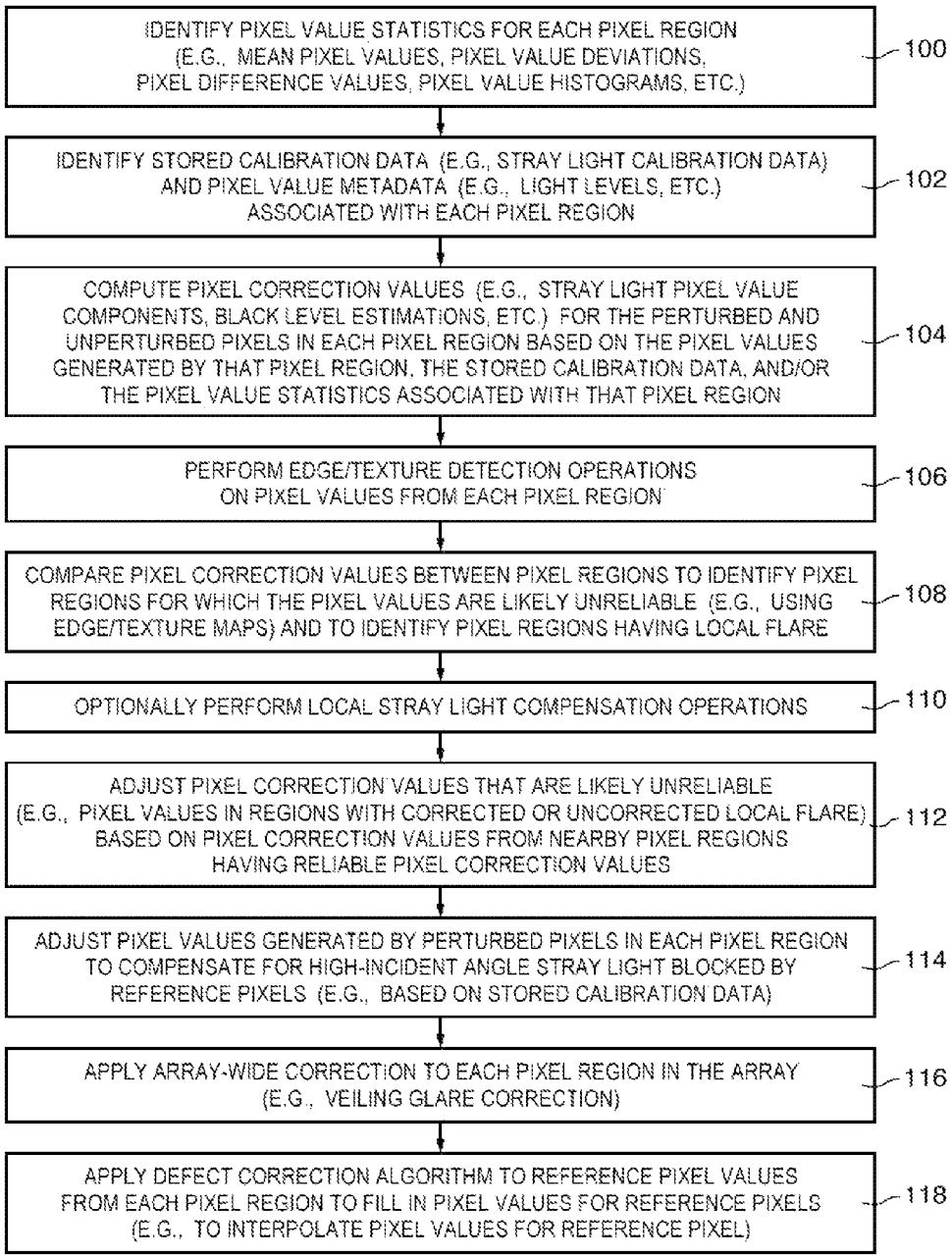
IDENTIFY PIXEL VALUE STATISTICS FOR EACH PIXEL REGION (E.G., MEAN PIXEL VALUES, PIXEL VALUE DEVIATIONS, PIXEL DIFFERENCE VALUES, PIXEL VALUE HISTOGRAMS, ETC.)
100
IDENTIFY STORED CALIBRATION DATA (E.G., STRAY LIGHT CALIBRATION DATA) AND PIXEL VALUE METADATA (E.G., LIGHT LEVELS, ETC.) ASSOCIATED WITH EACH PIXEL REGION
102
COMPUTE PIXEL CORRECTION VALUES (E.G., STRAY LIGHT PIXEL VALUE COMPONENTS, BLACK LEVEL ESTIMATIONS, ETC.) FOR THE PERTURBED AND UNPERTURBED PIXELS IN EACH PIXEL REGION BASED ON THE PIXEL VALUES GENERATED BY THAT PIXEL REGION, THE STORED CALIBRATION DATA, AND/OR THE PIXEL VALUE STATISTICS ASSOCIATED WITH THAT PIXEL REGION
104
PERFORM EDGE/TEXTURE DETECTION OPERATIONS ON PIXEL VALUES FROM EACH PIXEL REGION
106
COMPARE PIXEL CORRECTION VALUES BETWEEN PIXEL REGIONS TO IDENTIFY PIXEL REGIONS FOR WHICH THE PIXEL VALUES ARE LIKELY UNRELIABLE (E.G., USING EDGE/TEXTURE MAPS) AND TO IDENTIFY PIXEL REGIONS HAVING LOCAL FLARE
108
OPTIONALLY PERFORM LOCAL STRAY LIGHT COMPENSATION OPERATIONS
110
ADJUST PIXEL CORRECTION VALUES THAT ARE LIKELY UNRELIABLE (E.G., PIXEL VALUES IN REGIONS WITH CORRECTED OR UNCORRECTED LOCAL FLARE) BASED ON PIXEL CORRECTION VALUES FROM NEARBY PIXEL REGIONS HAVING RELIABLE PIXEL CORRECTION VALUES
112
ADJUST PIXEL VALUES GENERATED BY PERTURBED PIXELS IN EACH PIXEL REGION TO COMPENSATE FOR HIGH-INCIDENT ANGLE STRAY LIGHT BLOCKED BY REFERENCE PIXELS (E.G., BASED ON STORED CALIBRATION DATA)
114
APPLY ARRAY-WIDE CORRECTION TO EACH PIXEL REGION IN THE ARRAY (E.G., VEILING GLARE CORRECTION)
116
APPLY DEFECT CORRECTION ALGORITHM TO REFERENCE PIXEL VALUES FROM EACH PIXEL REGION TO FILL IN PIXEL VALUES FOR REFERENCE PIXELS (E.G., TO INTERPOLATE PIXEL VALUES FOR REFERENCE PIXEL)
118

FIG. 8

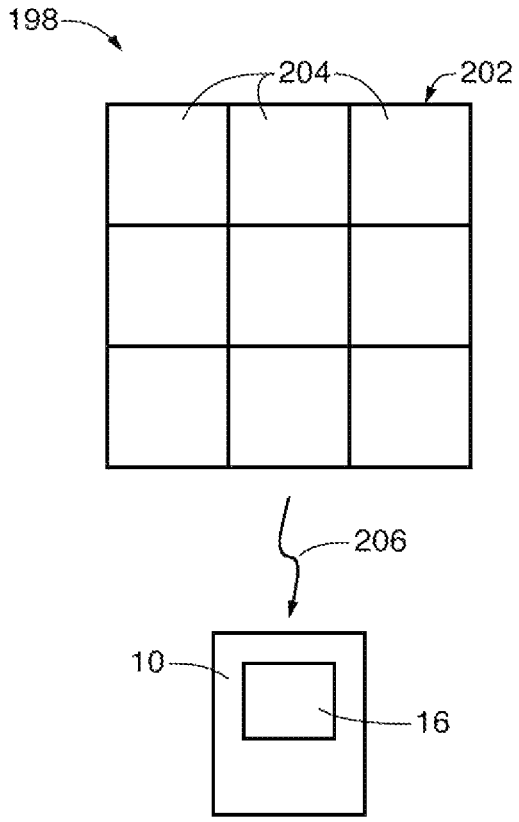

FIG. 9

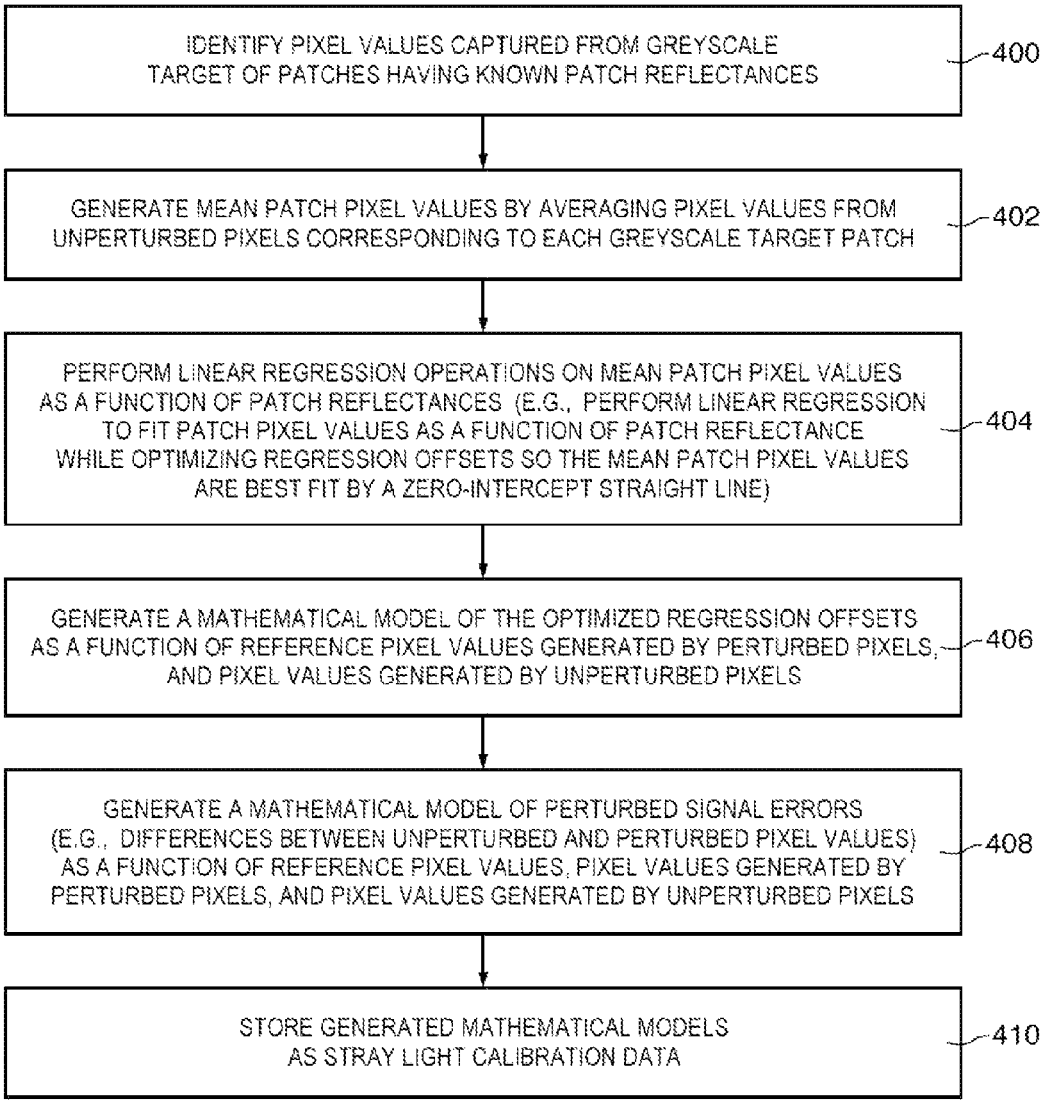
IDENTIFY PIXEL VALUES CAPTURED FROM GREYSCALE TARGET OF PATCHES HAVING KNOWN PATCH REFLECTANCES
400
GENERATE MEAN PATCH PIXEL VALUES BY AVERAGING PIXEL VALUES FROM UNPERTURBED PIXELS CORRESPONDING TO EACH GREYSCALE TARGET PATCH
402
PERFORM LINEAR REGRESSION OPERATIONS ON MEAN PATCH PIXEL VALUES AS A FUNCTION OF PATCH REFLECTANCES (E.G., PERFORM LINEAR REGRESSION TO FIT PATCH PIXEL VALUES AS A FUNCTION OF PATCH REFLECTANCE WHILE OPTIMIZING REGRESSION OFFSETS SO THE MEAN PATCH PIXEL VALUES ARE BEST FIT BY A ZERO-INTERCEPT STRAIGHT LINE)
404
GENERATE A MATHEMATICAL MODEL OF THE OPTIMIZED REGRESSION OFFSETS AS A FUNCTION OF REFERENCE PIXEL VALUES GENERATED BY PERTURBED PIXELS, AND PIXEL VALUES GENERATED BY UNPERTURBED PIXELS
406
GENERATE A MATHEMATICAL MODEL OF PERTURBED SIGNAL ERRORS (E.G., DIFFERENCES BETWEEN UNPERTURBED AND PERTURBED PIXEL VALUES) AS A FUNCTION OF REFERENCE PIXEL VALUES, PIXEL VALUES GENERATED BY PERTURBED PIXELS, AND PIXEL VALUES GENERATED BY UNPERTURBED PIXELS
408
STORE GENERATED MATHEMATICAL MODELS AS STRAY LIGHT CALIBRATION DATA
410

FIG. 10

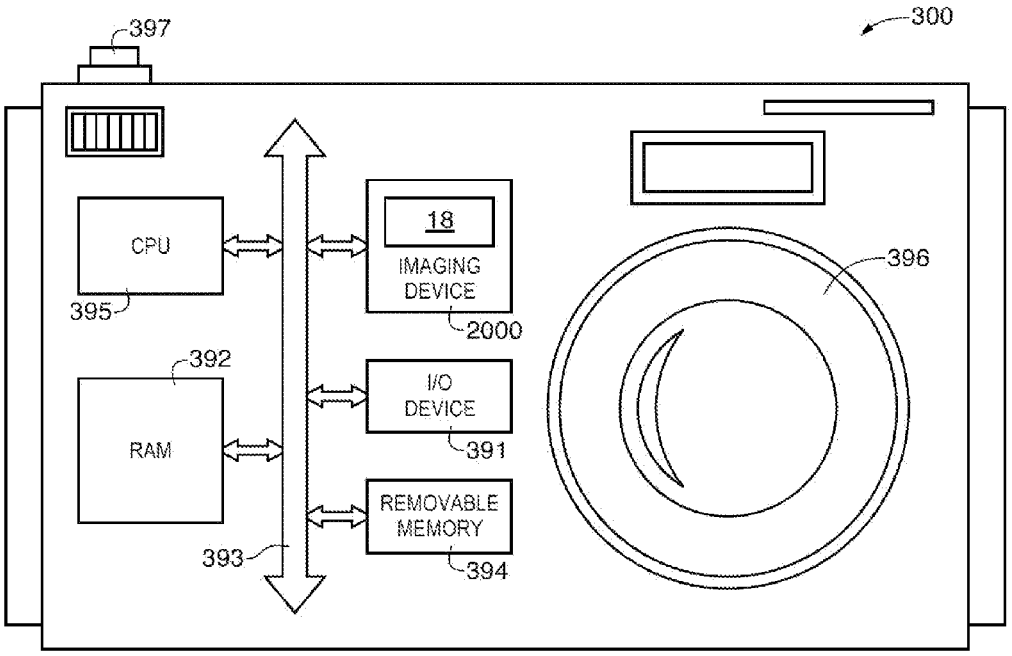
397
300
CPU
395
18
IMAGING DEVICE
2000
392
RAM
I/O DEVICE
391
REMOVABLE MEMORY
394
393
396

FIG. 11

IMAGING SYSTEMS WITH REFERENCE PIXELS FOR IMAGE FLARE MITIGATION

This application claims the benefit of provisional patent application No. 61/814,131, filed Apr. 19, 2013, which is hereby incorporated by reference herein in its entirety.

BACKGROUND

This relates generally to imaging devices, and more particularly, to imaging devices with clear image pixels.

Image sensors are commonly used in electronic devices such as cellular telephones, cameras, and computers to capture images. In a typical arrangement, an electronic device is provided with an array of image pixels arranged in pixel rows and pixel columns. Circuitry is commonly coupled to each pixel column for reading out image signals from the image pixels.

Light from objects in the field-of-view of an imaging system is typically focused onto the array of image pixels during image capture operations. In some situations, light from a light source that is inside or outside the field-of-view can enter the imaging system at a large angle of incidence or may travel along another path that results in multiple reflections within the optical system. This type of unwanted light can be reflected from one or more surfaces at which there are changes in refractive index in the imaging system before being absorbed by image pixels in the array, thereby generating flare artifacts in captured images.

It would therefore be desirable to be able to provide imaging devices with improved means of capturing and processing image signals.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a diagram of an illustrative electronic device having an imaging system with an image sensor and processing circuitry in accordance with an embodiment of the present invention.

FIG. **2** is a diagram of an illustrative pixel unit cell in an image sensor pixel array having clear filter pixels in accordance with an embodiment of the present invention.

FIG. **3** is a cross-sectional diagram of an illustrative pixel array having clear filter pixels in accordance with an embodiment of the present invention.

FIG. **4** is a cross-sectional diagram of an illustrative pixel array having a reference pixel with a black (opaque) color filter element for blocking direct image light in accordance with an embodiment of the present invention.

FIG. **5** is a cross-sectional diagram of an illustrative pixel array having a reference pixel with an opaque metal surface layer for blocking direct image light in accordance with an embodiment of the present invention.

FIG. **6** is a diagram of an illustrative pixel region in an image sensor pixel array having clear filter pixels and reference pixels for compensating for stray light in accordance with an embodiment of the present invention.

FIG. **7** is a diagram of an illustrative image sensor pixel array having an active region and an inactive region with a reference pixel for compensating for stray light in accordance with an embodiment of the present invention.

FIG. **8** is a flow chart of illustrative steps that may be performed by processing circuitry in an imaging system to compensate for stray light in an image sensor pixel array having clear filter pixels and reference pixels in accordance with an embodiment of the present invention.

FIG. **9** is a diagram of an illustrative calibration system for generating calibration data to be used by an imaging system to compensate for stray light effects in the imaging system in accordance with an embodiment of the present invention.

FIG. **10** is a flow chart of illustrative steps that may be performed by processing circuitry in an imaging system to generate calibration data for compensating for stray light in the imaging system in accordance with an embodiment of the present invention.

FIG. **11** is a block diagram of a processor system employing the embodiments of FIGS. **1-10** in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION

Electronic devices such as digital cameras, computers, cellular telephones, and other electronic devices include image sensors that gather incoming light to capture an image. The image sensors may include arrays of image sensor pixels. The pixels in an image sensor may include photosensitive elements such as photodiodes that convert the incoming light into digital pixel data. Image sensors may have any number of pixels (e.g., hundreds or thousands or more). A typical image sensor may, for example, have hundreds of thousands or millions of pixels (e.g., megapixels). Image sensors may include control circuitry such as circuitry for operating the image pixels and readout circuitry for reading out image signals corresponding to the electric charge generated by the photosensitive elements.

FIG. **1** is a diagram of an illustrative electronic device that uses an image sensor to capture images. Electronic device **10** of FIG. **1** may be a portable electronic device such as a camera, a cellular telephone, a video camera, or other imaging device that captures digital image data. Camera module **12** may be used to convert incoming light into electric charges and eventually into digital image data. Camera module **12** may include one or more lenses **14** and image sensor circuitry **16** (e.g., one or more image sensors **16**). Image sensor **16** may include arrays of image sensor pixels arranged in rows and columns such as a pixel array **18**. Image sensor pixels in pixel array **18** may, for example, be formed on a planar surface (e.g., parallel to the x-y plane of FIG. **1**) of a semiconductor substrate such as a silicon die. Image pixels in pixel array **18** may be controlled using pixel control circuitry **20**. During image capture operations, light from a scene may be focused onto pixel array **18** by lens **14**. Image sensor **16** may include any number of pixel arrays **18** (e.g., one pixel array, two pixel arrays, ten pixel arrays, etc.).

Image sensor pixels in pixel array **18** may generate pixel data (e.g., a respective pixel value generated by each image sensor pixel) in response to receiving light from a scene. For example, image sensor pixels in array **18** may include photosensitive elements such as photodiodes that convert incoming light into electric charge. Pixel control circuitry **20** may convert the electric charge into digital pixel data.

Image sensor **16** may receive control signals from storage and processing circuitry **22** and may supply pixel data to storage and processing circuitry **22**. Storage and processing circuitry **22** may include one or more integrated circuits (e.g., image processing circuits, microprocessors, storage devices such as random-access memory and non-volatile memory, etc.) and may be implemented using components that are separate from camera module **12** and/or that form part of camera module **12** (e.g., circuits that form part of an integrated circuit that includes image sensors **16** or an integrated circuit within module **12** that is associated with image sensor **16**).

If desired, calibration data **19** may be stored on storage and processing circuitry **22**. Calibration data **19** may, for example, include instructions for performing image processing operations on pixel data received from image sensor **16**, instructions for supplying control signals to image sensor **16**, or any other desired calibration information for performing image capture and processing operations using device **10**. Calibration data **19** may be generated and stored on storage and processing circuitry **22** prior to normal operations of device **10** (e.g., calibration data **19** may be generating during manufacture of image sensor **16**, during factory calibration of image sensor **16**, during assembly of device **10**, etc.).

Pixel array **18** may include a number of image sensor pixels arranged in rows and columns. Image sensor pixels in pixel array **18** may be provided with a color filter array having multiple color filter elements which allows a single image sensor to sample light of different colors. Image sensor pixels such as the image pixels in pixel array **18** are conventionally provided with a color filter array which allows a single image sensor to sample red, green, and blue (RGB) light using corresponding red, green, and blue image sensor pixels arranged in a Bayer mosaic pattern. The Bayer mosaic pattern consists of a repeating unit cell of two-by-two image pixels, with two green image pixels diagonally opposite one another and adjacent to a red image pixel diagonally opposite to a blue image pixel. However, limitations of signal to noise ratio (SNR) that are associated with the Bayer Mosaic pattern make it difficult to reduce the size of image sensors such as image sensor **16**. It may therefore be desirable to be able to provide image sensors with an improved means of capturing images.

In one suitable example that is sometimes discussed herein as an example, the green pixels in a Bayer pattern are replaced by clear image pixels as shown in FIG. **2**. As shown in FIG. **2**, pixel array **18** may have multiple image pixels **26** formed on a planar surface (e.g., parallel to the x-y plane of FIG. **2**). A repeating two-pixel by two-pixel unit cell **24** of image pixels **26** may be formed from two clear image pixels (C) (sometimes referred to herein as white image pixels) that are diagonally opposite one another and adjacent to a red (R) image pixel that is diagonally opposite to a blue (B) image pixel. Clear image pixels **26** in unit cell **24** may be formed with a visibly transparent color filter that transmits light across the visible light spectrum (e.g., clear pixels **26** can capture white light). Clear image pixels **26** may have a natural sensitivity defined by the material that forms the transparent color filter and/or the material that forms the image sensor pixel (e.g., silicon). The sensitivity of clear image pixels **26** may, if desired, be adjusted for better color reproduction and/or noise characteristics through use of light absorbers such as pigments. Pixel array **18** having clear image pixels **26** may sometimes be referred to herein as clear filter pixel array **18**.

Unit cell **24** may be repeated across clear filter pixel array **18** to form a mosaic of red, clear, and blue image pixels **26**. In this way, red image pixels may generate red image signals in response to red light, blue image pixels may generate blue image signals in response to blue light, and clear image pixels may generate clear image signals in response to white light. The clear signals may also be generated by the clear image pixels in response to any suitable combination of red, blue, and/or green light. For example, the red image signals may have a first spectral response value (e.g., an integrated signal power level as a function of the frequency of light received by red image sensor pixels), the blue image signals may have a second spectral response value, and the clear image signals may have a third spectral response value that is, for example, greater than seventy five percent of a sum of the first and second spectral response values (e.g., clear image signals may have a broad sensitivity for light received from an equal energy radiator over the visible light spectrum with standard CIE illuminant E).

The unit cell **24** of FIG. **2** is merely illustrative. If desired, any color image pixels may be formed adjacent to the diagonally opposing clear image pixels in unit cell **24** (e.g., the red image pixels in unit cell **24** may be replaced with blue image pixels, the blue image pixels in unit cell **24** may be replaced with red image pixels, the red image pixels in unit cell **24** may be replaced with yellow image pixels, etc.).

Clear image pixels **26** can help increase the signal-to-noise ratio (SNR) of image signals captured by image sensor **16** by gathering additional light in comparison with image pixels having a narrower color filter (e.g., a filter that transmits light over a subset of the visible light spectrum), such as green image pixels. Clear image pixels **26** may particularly improve SNR in low light conditions in which the SNR can sometimes limit the image quality of images. Image signals generated by clear filter pixel array **18** may be converted to red, green, and blue image signals to be compatible with circuitry and software that is used to drive most image displays (e.g., display screens, monitors, etc.). This conversion generally involves the modification of captured image signals using a color correction matrix (CCM).

In pixel arrays having clear image pixels such as clear filter pixel array **18**, stray light (sometimes referred to herein as high incident angle light) may propagate through image pixels **26** with minimal attenuation, often producing extraneous image signal in colored image pixels located adjacent to clear image pixels **26**. FIG. **3** is an illustrative cross-sectional diagram of clear filter pixel array **18** that shows how stray light may propagate through image pixels **26** in clear filter pixel array **18**.

As shown in FIG. **3**, pixel array **18** may include a clear image pixel **26-1** and a blue image pixel **26-2** (e.g., clear image pixel **26-1** and blue image pixel **26-2** arranged in a unit cell such as unit cell **24** of FIG. **2**). Each image pixel in pixel array **18** may include a corresponding color filter element **28** and photo-sensitive region **19** (e.g., clear image pixel **26-1** may include a clear color filter element **28-1** formed on an upper surface **29** of a first photo-sensitive region **19-1**, blue image pixel **26-2** may include a blue color filter element **28-2** formed on upper surface **29** of a second photo-sensitive region **19-2**, etc.). If desired, each image pixel **26** may include a respective microlens **27** formed on an upper surface **17** of the corresponding color filter element **28**.

During imaging operations, stray light (sometimes referred to herein as high incident angle light) and direct image light (sometimes referred to herein as proper imaging light or true imaging light) may be incident upon pixel array **18**. Direct image light may pass through upper surface **17** of the color filter **28** associated with a given pixel **26** prior to being received by the photosensitive region **19** associated with that image pixel. Stray light may be received by the photosensitive region **19** of a given image pixel **26** through adjacent image pixels **26** (e.g., stray light may pass through the color filter elements of other image pixels prior to being captured by the photosensitive region of a particular image pixel).

As shown in FIG. **3**, clear pixel **26-1** may receive direct image light **21** through upper surface **17** of clear color filter element **28-1** and blue pixel **26-2** may receive direct image light **21** through upper surface **17** of blue color filter **28-2**. Blue pixel **26-2** may receive stray light **23** through portions of clear pixel **26-1** (e.g., through microlens **27** and/or clear color filter element **28-1** associated with clear pixel **26-1**). Clear pixel **26-1** may receive stray light **25** through portions of blue

pixel **26-2**. In some situations, stray light such as stray light **23** and **25** originates outside the field-of-view of camera module **12** and is transmitted along a path through some or all of lenses **14** and onto image sensor **16** (FIG. **1**). In other situations, light that originates within the field-of-view of camera module **12** can also generate stray light **23** and **25** (e.g., light may encounter one or more changes in refractive index within camera module **12** such as interfaces between air and plastic or glass that cause some light to be reflected back from the interface and eventually onto the image sensor via multiple reflection paths).

Color filter elements **28** may attenuate direct light **21** and stray light **23** and **25**. For example, darker color filter elements may attenuate image light more than lighter color image lights. Clear color filter elements such as clear color filter element **28-1** may attenuate all colors of light less than colored color filter elements (e.g., green color filter elements, blue color filter elements such as blue color filter element **28-2**, etc.). Because light can pass through clear color filter **28-1** without being attenuated, more stray light is received at photosensitive region **19-2** of blue pixel **26-2** than would be received by blue pixel **26-2** if clear color filter element **28-1** were to be replaced with a colored color filter element (e.g., in scenarios where clear color filter element **28-1** is replaced with a colored color filter element such as a green color filter element, stray light **23** would be substantially attenuated by both filter elements **28-1** and **28-2** prior to being received by blue pixel photosensitive region **26-2**). In this scenario, blue pixel **26-2** may generate an erroneously high pixel value because stray **23** passes through clear filter element **28-1** and is un-attenuated prior to being passed through blue color filter element **28-2** and received photosensitive region **26-2** (e.g., blue pixel **26-2** may generate a greater pixel value when clear color filter element **28-1** is used than if clear color filter element **28-1** were to be replaced with a colored color filter element because clear color filter element **28-1** attenuates high stray light **23** less than a colored color filter element).

Stray light such as stray light **23** and **25** received by pixel array **18** may cause colored image pixels that are formed adjacent to clear image pixels **26** to generate erroneously high pixel values (e.g., erroneously high blue pixel values may be generated by blue image pixels adjacent to clear image pixels **26**, erroneously high red pixel values may be generated by red image pixels adjacent to clear image pixels **26**, etc.). In some situations in which a given colored image pixel should generate a black pixel value (e.g., because no light from the scene is incident upon that image pixel), stray light that passes through a clear image pixel adjacent to the given colored image pixel may cause that colored image pixel to record a positive pixel value even though no direct image light from the scene was incident upon upper surface **17** of that colored image pixel.

Stray light present in clear filter pixel array **18** may include localized stray light (e.g., stray light that affects only a subset of the pixels in array **18**) and global stray light (e.g., stray light that affects all pixels in array **18**). Global stray light that is approximately uniform across the entire pixel array **18** may sometimes be referred to herein as veiling glare. Local stray light that only affects a subset of the pixels in array **18** may sometimes be referred to as local flare. Veiling glare may be present for all image pixels **26** in clear filter pixel array **18** during normal imaging operations, whereas local flare may be produced when bright objects such as the sun or other bright lights illuminate only a portion of array **18** or are slightly outside the field of view of array **18**. Local flare can sometimes produce undesirable "ghost images" that are often colored. If care is not taken, un-attenuated stray light that is passed through clear image pixels **26** onto colored image pixels **26** (e.g., high-incident angle stray light **23** of FIG. **3**) can cause image sensor **16** to generate colored pixel signals for areas of the imaged scene that should be black, to incorrectly calculate image signals for other colors, and/or to produce localized color artifacts. It may therefore be desirable to be able to provide clear pixel imaging systems with improved methods for compensating for stray light captured by clear filter pixel array **18**.

In one suitable arrangement for compensating for stray light captured by image sensor **16**, clear filter pixel array **18** may include one or more so-called "reference pixels" distributed throughout the array. Reference pixels in clear filter pixel array **18** may be image pixels **26** that block direct image light **21** that is incident upon upper surface **17** of the associated pixel. In this way, reference pixels in clear filter pixel array **18** may generate pixel values in response to receiving stray light from adjacent image pixels and/or electronic crosstalk between the reference pixels and other image pixels in array **18** (e.g., reference pixels in array **18** may generate pixel values in response to stray light while filtering out direct image light). Pixel values generated by reference pixels in array **18** may be used by processing circuitry **18** to estimate a true black level of the imaged scene (e.g., local black levels of portions of the imaged scene) and to compensate for stray light in the imaging system (e.g., to mitigate local and global flare effects in captured image data).

This example is merely illustrative. In general, reference pixels in clear filter pixel array **18** may be formed as image pixels that filter out light received from any desired image light source. For example, reference pixels in clear filter pixel array **18** may be image pixels that filter out direct imaging light **23** (e.g., light incident upon upper surface **17** of the associated pixel), may be image pixels that filter out stray light received from adjacent image pixels, may be image pixels that filter out veiling glare light, may be image pixels that filter out combinations of these light sources, etc.

FIG. **4** is an illustrative cross-sectional diagram of clear filter pixel array **18** having a reference pixel formed adjacent to a colored image sensor pixel. As shown in FIG. **4**, reference pixel **30** may be formed adjacent to colored image sensor pixel **31**. Reference pixel **30** may have a substantially opaque color filter element **34** formed on upper surface **29** of photosensitive region **19-1**. Reference pixel **30** may, for example, be a clear image pixel such as clear image pixel **26-1** of FIG. **3** having opaque color filter element **34** in place of clear filter element **28-1**. Opaque color filter element **34** may be, for example, a black color filter element that substantially absorbs light received across the visible spectrum. If desired, opaque color filter element **34** may include a mixture of color filter array pigments (e.g., a mix of red and blue color filter array pigments). Direct image light **21** and stray light **23** incident upon upper surface **17** of reference pixel **30** may be blocked by opaque filter element **34** (e.g., opaque filter element **34** may substantially attenuate/filter direct image light **21** and stray light **23** across the visible spectrum).

Colored image pixel **31** may be formed adjacent to reference pixel **30** in clear filter pixel array **18**. For example, blue image pixel **26-2** (FIG. **3**) may be used as adjacent image pixel **31**. As shown in FIG. **4**, stray light **25** incident upon adjacent image pixel **31** may pass through blue color filter element **28-2** and may be blocked by opaque color filter element **34** in reference pixel **30**. As shown by FIG. **4**, a portion of the stray light incident upon array **18**, such as stray light **25**A incident upon adjacent image pixel **31**, may pass through blue color filter element **28-2** and may propagate to photosensitive region **19-1** of reference pixel **30** (e.g., stray

light **25**A may be propagate under opaque color filter element **34**). In this example, pixel values generated by reference pixel **30** may be a measure of the stray light incident on array **18** (e.g., a subset of the stray light incident on array **18** such as stray light **25**A) and electronic crosstalk (e.g., between reference pixel **30** and adjacent pixels in array **18**) that would have been recorded by a clear pixel formed at the location of reference pixel **30**, providing information that may be used by processing circuitry **22** for correcting for stray light and electronic crosstalk in array **18**. FIG. **4** is merely illustrative. If desired, adjacent image pixel **31** may be formed with any desired color filter element **28** (e.g., a red color filter element, a yellow color filter element, a green color filter element, etc.).

If desired, reference pixels **30** may be provided with a metal shield layer formed on upper surface **17** of clear filter element **28-1**, as shown in FIG. **5**. As shown in FIG. **5**, reference pixel **30** may be formed with a metal shield layer **35** formed at upper surface **17** of clear filter element **28-1** (e.g., metal layer **35** may be interposed between clear filter element **28-1** and microlens **27**). Metal shield layer **35** may, for example, be formed during the CMOS manufacturing process for pixel array **18**. Metal shield layer **35** may block direct image light **21** and stray light **23** incident upon surface **17** of reference pixel **30**. In this example, stray light **25** from adjacent pixel **31** may be captured by photo-sensitive region **19-1** of reference pixel **30**. The examples of FIGS. **4** and **5** are merely illustrative. If desired, reference pixels **30** may be formed with any desired structure for blocking direct image light at upper surface **17** (e.g., reference pixels **30** may be formed with any desired structure for blocking direct image light **21** from being captured by photosensitive region **19-1** of reference pixel **30**). The example of FIG. **5** is merely illustrative. If desired, metal shield layer **35** may be formed on upper surface **29** of photo-sensitive region **19-1** (e.g., shield layer **35** may be interposed between filter element **28-1** and region **19-1**) or at any other desired location in reference pixel **30**.

Pixel values generated by photosensitive regions **19** of image pixels **26** may include multiple pixel value components that are each generated in response to light received by photosensitive region **19** from a particular image source. For example, pixel values generated by adjacent pixel **31** may include a proper imaging light component, a stray light component, a veiling glare component, etc. Because stray light **23** is blocked from passing to adjacent image pixel **31** by reference pixels **30**, photosensitive region **19-2** of adjacent image pixels **31** may receive less stray light than other image pixels **26** in clear filter pixel array **18** that are not formed adjacent to a reference pixel **30**. Adjacent image pixels **31** may generate pixel values having stray light components (e.g., pixel value components generated in response to receiving stray light from adjacent image pixels) with a reduced magnitude relative to the stray light pixel value component generated by other image pixels **26** in pixel array **18** that are not formed adjacent to reference pixels **30**. Adjacent image pixels **31** may sometimes be referred to herein as perturbed image pixels **31**, because the stray light component of pixel values generated by adjacent image pixels **31** is "perturbed" relative to the stray light pixel value components other image pixels **26**. Image pixels **26** that are not adjacent to reference pixels **30** may sometimes be referred to herein as "unperturbed" image pixels **26**.

Reference pixels **30** may be distributed throughout pixel array **18**, as shown in FIG. **6**. As shown in FIG. **6**, pixel array **18** may include a number of repeating unit cell regions **32**. Each unit cell region **32** includes a number of repeating clear pixel unit cells **24**. Some clear pixels in pixel region **32** may be replaced with reference pixels **30** (e.g., a first reference pixel **30-1** and a second reference pixel **30-2**). If desired, reference pixels **30** may be uniformly scattered throughout pixel array **18**. For example, reference pixels **30** may be distributed throughout pixel region **32** at a uniform reference pixel density and with known reference pixel locations (e.g., processing circuitry **22** of FIG. **1** may store address locations of reference pixels **30**). Four perturbed pixels **31** may be located adjacent to each reference pixel **30**.

In the example of FIG. **6**, one reference pixel **30** is formed for every eight unit cells **24** (e.g., two reference pixels **30** are formed for every pixel region **32**). However, this is merely illustrative. If desired, any number of image pixels **26** in array **18** may be replaced with reference pixels **18** (e.g., seven percent of image pixels **26** in array **18** may be replaced with reference pixels **30**, less than seven percent of image pixels **26** in array **18** may be replaced with reference pixels **30**, three percent of image pixels **26** in array **18** may be replaced with reference pixels **30**, less than three percent of image pixels **26** in array **18** may be replaced with reference pixels **30**, etc.). For example, clear filter pixel array **18** may include a first number of image sensor pixels (e.g., a total number of perturbed pixels **31** and unperturbed pixels **26** in array **18**) and a second number of reference pixels **30**. The second number of reference pixels **30** may be less than or equal to three percent of the first number of image sensor pixels in array **18**. In general, a greater number of reference pixels **30** provides image sensor **16** with a better spatial sampling of stray light throughout pixel array **18** than a smaller number of reference pixels **30**, whereas a smaller number of reference pixels **30** may allow pixel array **18** to capture more image light than a greater number of reference pixels **30**.

In another suitable arrangement, a greater number of reference pixels may be formed along the periphery of pixel array **18** than in the middle of pixel array **18**. However, this is merely illustrative. If desired, reference pixels **30** may be scattered throughout pixel array **18** in any desired pattern and with any desired reference pixel density. In general, any number of colored or clear image pixels **26** may be replaced with reference pixels **30** (e.g., a subset of the blue image pixels **26** in array **18** may be replaced by reference pixels **30**, a subset of the red image pixels **26** in array **18** may be replaced by reference pixels **30**, a subset of clear image pixels **26** in array **18** may be replaced with reference pixels **30**, etc.).

In yet another suitable arrangement, reference pixels **30** may be formed on a portion of clear filter pixel array **18** that is outside of the image circle of lens **14** (FIG. **1**), as shown in FIG. **7**. As shown in FIG. **7**, pixel array **18** may include an active region **36** of image pixels **26** and an inactive region **37**. Active region **36** may be formed under image circle **38** of lens **14** (e.g., a circle of coverage of lens **14** as shown by dashed circle **38**). Stray light and direct image light transmitted by lens **14** is received by active region **36** of pixel array **18**, whereas inactive region **37** of pixel array **18** does not receive direct image light from lens **14**. If desired, reference pixel **30-3** may be formed in inactive region **37** (i.e., outside of image circle **38**). Because no direct image light is passed from lens **14** to reference pixel **30-3** in inactive region **37**, reference pixel **30-3** may generate pixel values in response to stray light. Pixel values generated by reference pixel **30-3** may be dominated by stray light noise. In this example, stray light received by reference pixel **30-3** may be correlated with stray light within the field of view **36** (e.g., using calibration data such as calibration data **19** of FIG. **1**). If desired, reference pixel **30-3** may be formed without an opaque filter element **34** (FIG. **3**) or metal shield layer **35** (FIG. **4**), because reference pixel **30-3** is located in inactive region **37** of pixel array **18**. If

desired, reference pixel **30-3** may be formed from the same image pixel architecture as the image pixels in active region **36** or may be formed from different image pixel architectures than those in active region **36**. For example, reference pixel **30-3** may be larger or simpler in design than the image pixels in active region **36**.

Perturbed image pixels **31** and unperturbed image pixels **26** may generate pixel values in response to direct image light and stray image light (e.g., direct image light **21** and stray image light **23** and **25** of FIGS. **4** and **5**). Pixel values generated by perturbed image pixels **31** and unperturbed image pixels **26** may include direct image light pixel value components (e.g., pixel value components generated in response to receiving direct image light **21** at the associated image pixel) and stray light pixel value components (e.g., pixel value components generated in response to receiving stray light **23** and/or **25** from other image pixels). In scenarios where local flare and veiling glare are present in an imaged scene, pixel values generated by pixel array **18** may include local flare pixel value components and veiling glare pixel value components. Pixel values generated by reference pixels **30**, perturbed image pixels **31**, and unperturbed image pixels **26** may be passed to storage and processing circuitry **22** for processing.

Storage and processing circuitry **22** may perform image processing operations on pixel values received from pixel array **18**. For example, storage and processing circuitry **22** may perform stray light compensation operations to mitigate the effects of image artifacts such as color artifacts, local flare artifacts, veiling glare artifacts, etc. in the received pixel values.

Pixel values generated by reference pixels **30** may sometimes be referred to herein as reference pixel values. Reference pixel values generated by reference pixels **30** may be used by storage and processing circuitry **22** to estimate a true black level of the captured pixel values. The true black level of the captured pixel values may be representative of the pixel values generated by image pixels **26** when no light is captured. Processing circuitry **22** may use the reference pixel values to adjust the captured pixel values to compensate for stray light in image sensor **16**.

FIG. **8** shows a flow chart of illustrative steps that may be performed by storage and processing circuitry **22** of FIG. **1** to perform stray light compensation operations on image data generated by clear filter pixel array **18**. Reference pixels **30** may generate reference pixel values primarily in response to stray light (e.g., reference pixels **30** may generate reference pixel values while blocking substantially all of the direct image light incident upon upper surface **17** of reference pixels **30**), whereas perturbed pixels **31** and unperturbed pixels **26** may generate pixel values in response to stray light and direct imaging light (e.g., pixels **26** and **30** may block no direct image light). For example, stray light components of the reference pixel values may be substantially greater than any direct image light components of the reference pixel values (e.g., reference pixel values may be dominated by stray light components whereas pixel values generated by pixels **32** and **26** may be dominated by direct image light components). Processing circuitry **22** may perform the steps of FIG. **8** after receiving pixel values from clear filter pixel array **18** for generating corrected pixel values that have been compensated for stray light in image sensor **16** (e.g., to mitigate the effects of local flare, veiling glare, etc. in the pixel values generated by clear filter pixel array **18**).

At step **100**, processing circuitry **22** may identify pixel values captured by pixels in each pixel region of clear filter pixel array **18** (e.g., pixel regions such as pixel region **32** of FIG. **6**). For example, processing circuitry **22** may identify reference pixel values generated by reference pixels **30** (e.g., reference pixel values generated in response to direct image light **21**), pixel values generated by perturbed image pixels **31**, and pixel values generated by unperturbed image pixels **26** (e.g., pixel values generated in response to direct image light **21** and stray light **23** and **25**) in each pixel region of array **18**.

Processing circuitry **22** may identify pixel value statistics associated with the pixel values captured by each pixel region in array **18**. For example, processing circuitry **22** may generate a histogram of pixel values for each pixel region and may compute mean pixel values, pixel value deviations, pixel value differences, or any other desired statistics associated with the pixel values captured by the corresponding pixel region (e.g., mean values of the pixel values captured by unperturbed image pixels **26** in each pixel region, difference values between the pixel values captured by perturbed pixels **31** and the reference pixel values in each pixel region, a mean value of pixel values captured by perturbed image pixels **31** in each pixel region, etc.). If desired, processing circuitry **22** may compare reference pixel values to pixel values captured by perturbed image pixels **31** and/or pixel values captured by unperturbed image pixels **26** for each pixel region.

At step **102**, storage and processing circuitry **22** may identify stored calibration data such as stray light calibration data **19** of FIG. **1**. Calibration data **19** may include, for example, mathematical models, a list of functions, coefficients, equations, or any other stray light calibration data that may be applied to captured pixel values to compensate for stray light in pixel array **18**. As an example, calibration data **19** may be generated during manufacture of image sensor **16** (e.g., prior to normal operation of image sensor **16** by an end user).

If desired, storage and processing circuitry **22** may identify metadata associated with pixel values captured by each pixel region in array **18**. Image sensor **16** and/or processing circuitry **22** may generate metadata for each pixel region. Metadata may include any desired metadata associated with captured pixel values, such as scene light level (e.g., a global light level for the entire pixel array **18** and/or local light levels for each pixel region), whether an excessively bright object is within a given pixel region (e.g., the sun or other bright light sources), signal-to-noise ratio, exposure times, etc.

At step **104**, processing circuitry **22** may determine the level of unwanted signal in the pixel values generated by each pixel region in array **18** (e.g., unwanted signal generated in response to local and/or global stray light). Processing circuitry **22** may compute pixel correction values for perturbed pixels **31** and unperturbed pixels **26** in each pixel region based on the reference pixel values, stored calibration data **19**, and/or the identified pixel value statistics for each pixel region. The pixel correction values may, for example, compensate for the unwanted signal in the captured pixel values (e.g., the pixel correction values may be offset pixel values that are indicative of the amount of unwanted signal in the captured pixel values).

If desired, processing circuitry **22** may compute pixel correction values by applying calibration data **19** to the captured pixel values and the pixel value statistics. For example, processing circuitry **22** may compute pixel correction values for perturbed pixels **31** and unperturbed pixels **26** as a linear combination of the reference pixel values, the pixel value statistics (e.g., the mean pixel value generated by unperturbed pixels **26**) and the pixel values generated by perturbed pixels **31** and/or unperturbed pixels **26** (e.g., using linear weights specified by calibration data **19**, using mathematical models specified by calibration data **19**, etc.). As another example,

processing circuitry **22** may compute the pixel correction values for perturbed pixels **31** as a sum between the reference pixel values and a given function of the pixel values generated by perturbed pixels **31** and/or unperturbed pixels **26** (e.g., using mathematical models and coefficients specified by calibration data **19**). The pixel correction values may, for example, be estimates of the stray light pixel value components generated by perturbed pixels **31** and unperturbed pixels **26**. In general, the pixel correction values may be computed as any desired function of the captured pixel values and the identified pixel value statistics (e.g., based on mathematical models specified by calibration data **19**).

At step **106**, processing circuitry **22** may perform edge and/or texture detection operations on the pixel values captured by each pixel region of array **18**. Processing circuitry **22** may determine whether there are any pixel value edges in the pixel values captured by each region and/or whether pixel values captured by each pixel region are within a texture area of the captured image (e.g., an area of the captured image having a relatively large number of edges of objects from the imaged scene). Processing circuitry **22** may perform texture detection operations using any desired texture detection algorithm (e.g., by applying spatial filters to the pixel values captured by pixel array **18**). If desired, processing circuitry **22** may generate edge and/or texture maps for the pixel values in each pixel region. In some cases, pixel values that include edges and/or texture areas may cause processing circuitry **22** to generate inaccurate pixel values when correcting for local stray light in the captured pixel values.

At step **108**, processing circuitry **22** may compare the pixel correction values generated for each pixel region in array **18**. If desired, processing circuitry **22** may identify pixel regions for which the pixel correction values are likely to be unreliable (e.g., using the edge/texture maps generated associated with that pixel region). For example, processing circuitry **22** may determine that pixel regions having excessive textures and/or edges have unreliable pixel correction values (e.g., because pixel values that include edges and/or texture areas may cause processing circuitry **22** to generate inaccurate pixel values when correcting for local stray light in the captured pixel values). Processing circuitry **22** may label pixel correction values from pixel regions having excessive texture and/or edge areas as unreliable. If desired, processing circuitry **22** may label outlier pixel correction values that deviate excessively with respect to the other pixel correction values in array **18** (e.g., that deviate excessively with a mean pixel correction value for array **18**) as unreliable pixel correction values.

Processing circuitry **22** may identify pixel regions in array **18** having local flare effects. For example, processing circuitry **22** may detect local flare artifacts in the pixel values from each pixel region. Processing circuitry **22** may determine whether local flare is present in a given pixel region based on the identified metadata (e.g., processing circuitry **22** may determine that local flare is present in a given pixel region if the metadata indicates that there is a bright object at or near the field of view of that pixel region).

At step **110**, processing circuitry **22** may optionally perform local stray light compensation operations for each pixel region in array **18**. For example, processing circuitry **22** may perform local stray light compensation operations on pixel regions that do not have any texture or edge areas or on pixel regions that do not have any outlier pixel correction values. As another example, processing circuitry **22** may perform local stray light compensation operations on pixel values that were identified as having local flare effects (e.g., during processing of step **108**). If desired, processing circuitry **22** may omit local stray light compensation operations on pixel regions having excessive texture and/or edge areas (e.g., as illustrated by the generated edge/texture maps). Processing circuitry **22** may omit local stray light compensation operations on pixel regions that do not include any local flare effects.

If desired, processing circuitry **22** may perform local stray light compensation operations (e.g., local flare correction) on the pixel values generated by perturbed pixels **31** and/or unperturbed pixels **26** in a given pixel region (e.g., using the calculated pixel correction values). Processing circuitry may perform local flare correction using any desired local flare correction algorithm. For example, processing circuitry **22** may subtract the calculated pixel correction values from the pixel values generated by perturbed image pixels **31** and/or unperturbed image pixels **26**. In this way, processing circuitry **22** may mitigate local flare effects and artifacts present in the pixel values generated by perturbed image pixels **31** and unperturbed image pixels **26**.

At step **112**, processing circuitry **112** may adjust pixel correction values that were determined to be unreliable (e.g., determined to be unreliable while processing step **108**). For example, processing circuitry **22** may perform smoothing operations on the pixel correction values computed for pixel regions having unreliable pixel correction values. For example, processing circuitry **22** may replace the computed pixel correction values for a given pixel region (e.g., processing circuitry **22** may replace the pixel correction values for the given pixel region with reliable pixel correction values from adjacent pixel regions in array **18**, may replace the pixel correction values for region **32** with interpolated pixel correction values, or may replace the pixel correction values for region **32** with any other desired pixel correction values). In this way, processing circuitry **22** may compensate for any outlier pixel correction values computed for each pixel region in array **18**.

At step **114**, processing circuitry **22** may generate perturbed pixel correction values for perturbed pixels **31** in each pixel region of clear filter pixel array **18**. The generated perturbed pixel correction values may be based on the stray light that is blocked from perturbed pixels **31** by reference pixels **30**. For example, processing circuitry **22** may compute the perturbed pixel correction values based on the captured pixel values and calibration data such as calibration data **19** as shown in FIG. **1** (e.g., using mathematical models of perturbed signal errors in calibration data **19**). Processing circuitry **22** may adjust the pixel values generated by perturbed image pixels **31** in each image region of array **18** using the perturbed pixel correction values. In this way, processing circuitry **22** may compensate for the stray light **23** (FIG. **4**) that is blocked by reference pixels **30** (e.g., to ensure that the stray light component of pixel values generated by perturbed pixel values **31** is consistent with that of unperturbed image pixels **26**).

At step **116**, processing circuitry **22** may perform array-wide correction operations on pixel values from each pixel region in array **18**. For example, processing circuitry **22** may perform veiling glare compensation operations or any other desired global correction operations to the pixel values generated across pixel array **18**. For pixel regions having excessive texture and/or edge areas, processing circuitry **22** may perform veiling glare compensation operations on those pixel regions in response to determining that those pixel regions have excessive texture and/or edge areas. If desired, processing circuitry **22** may uniformly adjust the pixel values captured by perturbed pixels **31** and/or unperturbed pixels **26** across array **18** by an offset value (e.g., a veiling glare correction value, estimated black level, or any other desired

correction value associated with array-wide pixel value correction). In this way, processing circuitry **22** may compensate for stray light that is uniform across array **18** (e.g., veiling glare) in the pixel values generated by clear filter pixel array **18**.

At step **118**, processing circuitry **22** may perform defect correction operations on the reference pixel values gathered by reference pixels **30** in each pixel region of clear filter pixel array **18**. Processing circuitry **22** may perform defect correction operations on the reference pixel values by replacing the reference pixel values with corrected reference pixel values. For example, processing circuitry **22** may replace reference pixel values generated by reference pixels **30** with interpolated pixel values that are computed by interpolating the pixel values generated by perturbed image pixels **31** and/or unperturbed image pixels **26**. In another suitable arrangement, circuitry **22** may replace reference pixel values generated by reference pixels **30** with interpolated pixel values that are computed by interpolating stray light-corrected pixel values computed for perturbed image pixels **31** and/or unperturbed image pixels **26**.

In this way, processing circuitry **22** may produce corrected pixel values for each pixel in pixel array **18** (e.g., for each reference pixel **30**, perturbed pixel **31**, and unperturbed pixel **26**) that have been compensated for any stray light (e.g., to mitigate the effects of local flare, veiling glare, etc.). Processing circuitry **22** may subsequently use the corrected pixel values to perform accurate image processing operations (e.g., gamma correction operations, white balance operations, color correction operations, demosaicking operations, for read out as a final image signal, etc.).

Image sensor **16** may be tested and calibrated using a test system for generating calibration data **19**. As shown in FIG. **9**, device **10** may be calibrated using calibration system **198**. Image sensor **16** may be calibrated prior to normal device operation (e.g., normal operation of device **10** by an end user). For example, image sensor **16** may be calibrated in calibration system **198** during manufacture of image sensor **16** and/or device **10**, prior to assembly of device **10**, etc. Calibration system **198** may include a greyscale target of patches **204**. During calibration operations, image sensor **16** in device **10** may receive light **206** from a greyscale target **202** (e.g., light **206** may be reflected off of greyscale target **202**). Greyscale target **202** may include any desired number of greyscale patches **204**. Greyscale target **202** may, for example, be a poster or other visual target having multiple greyscale patches **204** that are each colored a different shade of grey, from white to black.

Greyscale target **202** may have multiple predetermined properties from which to calibrate the imaging performance of image sensor **16**. For example, each patch **204** in greyscale target **202** may have a known reflectance value that is indicative of the percentage of incoming light that is reflected off of the associated patch **204**. For example, darker patches **204** may have lower reflectance values than lighter patches **204**. Storage and processing circuitry **22** on device **10** may store instructions for performing calibration operations for generating calibration data **19**. For example, processing circuitry **22** may store calibration software or other calibration instructions for generating calibration data **19**. The example of FIG. **9** is merely illustrative. If desired, device **10** may be coupled to an external calibration host (e.g., a personal computer, laptop computer, or other desired calibration equipment) for performing calibration operations. In this arrangement, the external host may provide calibration control signals to device **10** for performing calibration operations.

FIG. **10** shows a flow chart of illustrative steps that may be performed by storage and processing circuitry **22** on device **10** for generating stray light calibration data **19** (FIG. **1**). The steps of FIG. **10** may, for example, be performed by processing circuitry **22** during assembly of device **10**, during manufacture of image sensor **16**, or at any other desired time prior to normal operation of device **10** (e.g., prior to use of device **10** by an end user). The steps of FIG. **10** may be performed by storage and processing circuitry **22** after pixel array **18** in image sensor **16** generates pixel values in response to light received from greyscale target **202** (e.g., in response to light reflected off of greyscale target **202**).

At step **400**, processing circuitry **22** may identify pixel values received from image sensor **16** corresponding to each patch **204** of greyscale target **202**. For example, processing circuitry **22** may identify a first set of pixel values corresponding with a first greyscale patch **204**, a second set of pixel values corresponding with a second greyscale patch **206**, etc. Processing circuitry **22** may identify reference pixel values and pixel values captured by perturbed image pixels **31** and unperturbed pixels **26** (FIG. **6**) for each greyscale patch **204**.

At step **402**, processing circuitry **22** may generate a respective mean patch pixel value for each greyscale patch **204** by averaging the pixel values captured by each unperturbed pixel **26** in the associated greyscale patch. In the example of FIG. **9** in which greyscale target **202** has nine patches **204**, nine mean patch pixel values may be computed using unperturbed pixel values **26** in pixel array **18**.

At step **404**, processing circuitry **22** may perform linear regression on the mean patch pixel values as a function of patch reflectance value. The intercept obtained from this linear regression may be approximately equal to the desired veiling glare correction value. While performing linear regression on the mean patch pixel values, processing circuitry **22** may optimize offset values (e.g., intercept values) of the linear regression so that the mean patch pixel values are best fit by a zero-intercept straight line in patch reflectance space (e.g., processing circuitry **22** may perform linear regression operations on the mean pixel values as a function of the predetermined reflectance values by fitting the mean pixel values with a zero-intercept straight line).

At step **406**, processing circuitry **22** may generate a mathematical model of the optimized regression offset values (e.g., the desired veiling glare correction values) as a function of reference pixel values, pixel values generated by perturbed pixels **31**, and pixel values generated by unperturbed pixels **26**. For example, the mathematical model may be a function or group of functions that depend on the gathered pixel values. The mathematical model may be subsequently used during normal operation of device **10** to generate pixel correction values for unperturbed pixels **26**.

At step **408**, processing circuitry **22** may generate a mathematical model of perturbed signal errors associated with the pixel values generated by perturbed pixels **31** as a function of reference pixel values and pixel values generated by unperturbed pixels **26**. For example, processing circuitry **22** may model the difference between pixel values generated by perturbed pixels **31** and pixel values generated by unperturbed pixels **26**. The mathematical model of perturbed signal errors may, for example, model the high incident angle light such as light **23** (FIG. **4**) that is blocked from being captured by perturbed pixels **31** by reference pixels **30**. The mathematical model of perturbed signal errors generated while processing step **408** may be used during normal device operation by processing circuitry **22** to generate perturbed pixel correction values for perturbed image pixels **31** (e.g., while performing step **114** of FIG. **8**).

At step **410**, processing circuitry **22** may store the generated mathematical models as calibration data **19** for use during normal operation of image sensor **16**.

FIG. **11** shows in simplified form a typical processor system **300**, such as a digital camera, which includes an imaging device **2000** (e.g., an imaging device **2000** such as imaging sensor **16** and storage and processing circuitry **22** of FIGS. **1-10** employing clear color filters, reference pixels, and the techniques for operations described above). The processor system **300** is exemplary of a system having digital circuits that could include imaging device **2000**. Without being limiting, such a system could include a computer system, still or video camera system, scanner, machine vision, vehicle navigation, video phone, surveillance system, auto focus system, star tracker system, motion detection system, image stabilization system, and other systems employing an imaging device.

The processor system **300** generally includes a lens **396** for focusing an image on pixel array **18** of device **2000** when a shutter release button **397** is pressed, central processing unit (CPU) **395**, such as a microprocessor which controls camera and one or more image flow functions, which communicates with one or more input/output (I/O) devices **391** over a bus **393**. Imaging device **2000** also communicates with the CPU **395** over bus **393**. The system **300** also includes random access memory (RAM) **392** and can include removable memory **394**, such as flash memory, which also communicates with CPU **395** over the bus **393**. Imaging device **2000** may be combined with the CPU, with or without memory storage on a single integrated circuit or on a different chip. Although bus **393** is illustrated as a single bus, it may be one or more busses or bridges or other communication paths used to interconnect the system components.

Various embodiments have been described illustrating imaging systems and methods of operating image systems having an array of image sensor pixels and reference pixels for mitigating the effects of image flare produced in the imaging system.

An imaging system may include an array of image sensor pixels having one or more reference pixels distributed throughout the image sensor pixels in the array. For example, the reference pixels may be formed in place of one or more image sensor pixels in the array.

The imaging system may include a lens for focusing an image onto the array of image sensor pixels and processing circuitry. The array of image sensor pixels may receive direct image light and stray light from the lens. The lens may pass direct image light onto the array within an image circle of the lens. If desired, the reference pixels may be located at a portion of the array that is outside of the image circle of the lens. The image sensor pixels may generate pixel values in response to the direct image light and the stray light and the reference pixels may generate reference pixel values in response to the stray light (E.g., stray light received through at least one of the image sensor pixels). The processing circuitry may adjust the pixel values based on the reference pixel values for mitigating the effects of image flare in the imaging system.

The reference pixels may include a photosensitive region and an opaque color filter element formed on an upper surface of the photosensitive region. The opaque color filter element may block direct image light from being received by the photosensitive region. The image sensor pixels and may include color filter elements. The color filter elements and opaque color filter elements may be arranged in a color filter array having repeating groups (e.g., repeating unit cells) of color filter elements.

The processing circuitry may perform stray light compensation operations on the pixel values based on the pixel values, the reference pixel values, statistics associated with the pixel values, calibration data stored on the processing circuitry, etc. For example, the processing circuitry may perform local flare compensation operations on the pixel values and/or veiling glare compensation operations on the pixel values to mitigate the effects of stray light in the imaging system. The processing circuitry may compute pixel correction values that have been compensated for local flare and/or veiling glare for the pixel values. If desired, the processing circuitry may compute perturbed pixel correction values for pixels adjacent to the reference pixels in the array that compensates for light that is blocked by the opaque color filter element.

If desired, the imaging system may be calibrated using a calibration system that includes a calibration target of greyscale patches. The greyscale patches may have predetermined reflectance values. The array may generate respective sets of pixel values and reference pixel values for each of the greyscale patches and the processing circuitry may generate respective sets of mean pixel values for each of the greyscale patches. The processing circuitry may perform linear regression operations by generating linear regression offset values for the mean pixel values as a function of the predetermined reflectance values and may generate the calibration data for the imaging device based on the linear regression offset values.

The imaging system with a clear filter pixel array and reference pixels and the associated techniques for compensating for stray light in the imaging system may be implemented in a system that also includes a central processing unit, memory, input-output circuitry, and an imaging device that further includes a pixel array, and a data converting circuit.

The foregoing is merely illustrative of the principles of this invention and various modifications can be made by those skilled in the art without departing from the scope and spirit of the invention. The foregoing embodiments may be implemented individually or in any combination.

What is claimed is:

1. A method for operating an imaging system having processing circuitry and an array of image sensor pixels, wherein the array of image sensor pixels includes a reference pixel, the method comprising:

with the array of image sensor pixels, receiving direct image light and stray light;

with the image sensor pixels, generating pixel values in response to the direct image light and the stray light;

with the reference pixel, generating a reference pixel value primarily in response to the stray light; and

with the processing circuitry, adjusting the pixel values generated by the image sensor pixels based on the reference pixel value generated by the reference pixel, wherein adjusting the pixel values comprises:

determining whether the pixel values comprise a texture area; and

in response to determining that the pixel values comprise a texture, performing veiling glare compensation operations on the pixel values.

2. The method defined in claim **1**, wherein the reference pixel comprises a photosensitive region, wherein the image sensor pixels include color filter elements, and wherein generating the reference pixel value primarily in response to the stray light comprises:

generating the reference pixel value in response to receiving the stray light at the photosensitive region of the reference pixel through at least one of the color filter elements.

3. The method defined in claim **2**, wherein the reference pixel further comprises a black color filter element, the method further comprising:

with the black color filter element, blocking the direct image light.

4. The method defined in claim **2**, wherein the reference pixel further comprises a reference pixel color filter element having a metal layer, the method further comprising:

with the metal layer, blocking the direct image light.

5. The method defined in claim **2**, wherein the imaging system comprises a lens, the method further comprising:

with the lens, passing the direct image light onto the array of image sensor pixels within an image circle of the lens, wherein the reference pixel is located on a portion of the array outside of the image circle of the lens.

6. The method defined in claim **2**, wherein the processing circuitry is configured to store stray light calibration data and wherein adjusting the pixel values comprises:

performing local flare compensation operations on the pixel values based on the reference pixel value and the stray light calibration data.

7. The method defined in claim **6**, wherein adjusting the pixel values further comprises:

performing veiling glare compensation operations on the pixel values.

8. The method defined in claim **6**, wherein performing the local flare compensation operations comprises:

identifying pixel value statistics associated with the pixel values; and

computing pixel correction values based on the reference pixel value, the identified pixel value statistics, and the stray light calibration data.

9. The method defined in claim **8**, wherein performing the local flare compensation operations further comprises:

identifying pixel value metadata associated with the pixel values; and

computing the pixel correction values based on the pixel value metadata.

10. The method defined in claim **9**, wherein the pixel value metadata comprises signal-to-noise ratio information and wherein performing the local flare compensation operations further comprises:

computing the pixel correction values based on the signal-to-noise ratio information.

11. The method defined in claim **9**, wherein the pixel value metadata comprises light level information and wherein performing the local flare compensation operations further comprises:

computing the pixel correction values based on the light level information.

12. The method defined in claim **8**, wherein the reference pixel comprises an opaque color filter element and wherein computing the pixel correction values comprises:

computing a perturbed pixel correction value for an image sensor pixel located adjacent to the reference pixel that compensates for light that is blocked by the opaque color filter element.

13. The method defined in claim **2**, wherein the color filter elements of the image sensor pixels comprise clear color filter elements.

14. A method for operating an imaging system having processing circuitry and an array of image sensor pixels, wherein the array of image sensor pixels includes a reference pixel, the method comprising:

with the array of image sensor pixels, receiving direct image light and stray light;

with the image sensor pixels, generating pixel values in response to the direct image light and the stray light;

with the reference pixel, generating a reference pixel value primarily in response to the stray light; and

with the processing circuitry, adjusting the pixel values generated by the image sensor pixels based on the reference pixel value generated by the reference pixel, wherein adjusting the pixel values comprises:

determining whether the pixel values comprise an edge area; and

in response to determining that the pixel values comprise an edge area, performing veiling glare compensation operations on the pixel values.

15. The method defined in claim **14**, further comprising:

with the processing circuitry, replacing the reference pixel value with an interpolated pixel value.

16. The method defined in claim **14**, wherein the reference pixel comprises a photosensitive region, wherein the image sensor pixels include color filter elements, and wherein generating the reference pixel value primarily in response to the stray light comprises:

generating the reference pixel value in response to receiving the stray light at the photosensitive region of the reference pixel through at least one of the color filter elements.

17. A system, comprising:

a central processing unit;

memory;

input-output circuitry; and

an imaging device, wherein the imaging device comprises:

an array of image sensor pixels arranged in rows and columns, wherein the array includes a reference pixel;

a lens that focuses an image onto the array within an image circle of the lens, wherein image sensor pixels in the array that are within the image circle of the lens are configured to receive direct image light and stray light from the lens, wherein the image sensor pixels within the image circle of the lens are configured to generate pixel values in response to the direct image light and the stray light, wherein the reference pixel is located in the array and outside of the image circle of the lens and is configured to generate a reference pixel value in response to the stray light, and wherein the reference pixel is formed without any opaque light shielding elements that shield the reference pixel from the direct light; and

processing circuitry configured to adjust the pixel values based on the reference pixel value.

18. The system defined in claim **17**, wherein the image sensor pixels comprise clear color filter elements.

19. The system defined in claim **18**, wherein the clear color filter elements are arranged in a color filter array, wherein the color filter array comprises repeating groups of red color filter elements, blue color filter elements, and the clear color filter elements.

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